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A CLOSED-CYCLE SYSTEM FOR GAS BEARINGS

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I. INTRODUCTION

The support of sensing masses of inertial instruments by gas lubrication and flotation has considerable inherent advantages. The virtual elimination of starting friction and of drifts caused by anisoelastic effects and mass shifts is a typical example. If missions of short duration are involved, as is the case in missile or booster applications, the required supply of compressed gas can readily be stored in suitable containers in the vehicle. However, in missions of long duration, such as lunar or planetary explorations, the storage of expendable gas becomes impractical because of the size and weight of the container. A closed-cycle system in which the gas is recirculated then becomes mandatory.

The severe constraints on energy sources available in space vehicles are of prime importance in the selection of a regenerative-gas-supply system. Direct utilization of thermal energy, without conversion to electrical and mechanical power and its attendant low efficiency, is obviously preferable to electromechanical systems.

*This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. NASw-6, sponsored by the National Aeronautics and Space Administration.

For example, if an efficiency of 30% is assumed for motor-driven compressors or pumps and of 10% for thermoelectric cells converting solar radiation into electric power, an over-all efficiency of 3% can be attained. If, however, a system employing thermal power is used for the recirculation pumping of a gas or vapor, solar radiation or thermal energy from a nuclear reactor can be applied and, by saving the conversion losses, the power requirement can be reduced very substantially. These considerations have resulted in a study of the feasibility and performance characteristics of a thermally pumped closed-cycle vapor system for gas-lubricated bearings and gas-floated inertial instruments in space vehicles.

A regenerative system of this type is shown schematically in Fig. 1. It consists of an evaporator in which a suitable fluid is vaporized and raised to the required operating pressure. A pressure regulator keeps the pressure at a set value and a superheater raises the temperature sufficiently above the dew point to avoid condensation at the temperature of the gas bearing. After passing through the bearing, the vapor is condensed and the condensate pumped back into the evaporator.

II. FREON VAPOR SYSTEM

The selection of a suitable fluid for a closed-cycle system is influenced by a number of considerations. The fluid must be inert with respect to the materials used in the construction of gas bearings and inertial sensors such as steel, aluminum,etc., and gasket materials such as neoprene; it should be nonexplosive, nonflammable, and of low toxicity. Its specific heat and heat of vaporization should be as low as possible to minimize the energy required to raise it to operating pressure. It should also be chemically very stable and have low viscosity, since the friction torque is proportional to the latter.

These specifications are satisfied by a number of the Freon compounds. Figure 2 shows the pressure—temperature relationship of various Freon compounds (as published by the DuPont Company). It will be noted that the pressure of Freon-113, for example, can be increased from 0 to 50 psig by raising the temperature from 118°F to 214°F. The temperature range can be shifted to suit various environmental conditions. For instance, using Freon-114 instead of Freon-113, the same pressure increase of 50 psig can be produced by raising the temperature from 38°F to 122°F. The Freon system can thus readily be optimized with respect to ambient conditions, i.e., temperatures in the payload compartment and the solar radiation panel.

The gas consumption of an externally pressurized bearing depends on its design and, in particular, on the number and size of its orifices and the height of the gap. The supply pressure depends on the load-carrying capacity and stiffness required. A typical journal gas bearing, to support the gimbal axis of a single-axis gyro, will consume approximately 0.7 cfm of air at 32 psig plenum pressure if rows of orifices are used as pressure regulators and approximately 0.15 cfm if slits serve the same purpose. A gas-floated spinning sphere which may be employed as a stable reference or as a momentum-transfer means for attitude control can be operated with a substantially lower flowrate, i.e., approximately 0.05 cfm, since it can be supported by four or six pressure pads with a single orifice each.

III. EXPERIMENTS

In order to determine the thermal power required within the range of the above flowrates and pressures, data were taken on an experimental closed-cycle system, which is shown in Fig. 3. A dome-shaped vessel is filled about one-half with liquid Freon into which a pancake-shaped Chromalox heater coil is immersed. The power input to the heater can be controlled by a regulating transformer (Variac) and is measured by a wattmeter, as shown in Fig. 4. The flowrate of the fluid in the vapor phase and in the liquid phase is measured by variable-orifice-type flowmeters. The temperature and pressure distribution in the system is determined by thermocouples (TC) and pressure transducers which are connected to a recording instrument, as shown in Fig. 4.

The gas bearing was simulated in the experiments by a regulating valve whose rate of flow and pressure drop could be adjusted within the required range. It was enclosed, together with the evaporator and gas flowmeter, in a wooden housing filled with vermiculite for better insulation.

In each series of tests the vapor flowrate through the simulating valve was held constant and measured on the downstream side, i.e., at atmospheric pressure. The wattage input to the heater coil was varied and readings of the pressure and temperature were taken at the points indicated in Fig. 4 after the steady-state condition was reached.

The results of some of the experiments with Freon-114 are shown in Fig. 5 and 6. Figure 5a is a plot of the measured power input to the heater as a function of the pressure drop across the simulator valve, for a range of flowrates from 0.1025 to 0.41 cfm (at atmospheric pressure), which corresponds to the gas consumption of slit-type journal bearings. Figure 5b was derived from 5a and shows the power as a function of the flowrate with the pressure as a parameter. Corresponding plots for low flowrates, i.e., from 0.0211 to 0.0478 cfm, typical for the gas consumption of a multiple-pad suspension system, are shown in Fig. 6a and b.

The wattage measurements plotted in Fig. 6 do not include the heat input required to raise the temperature of the liquid Freon from the condensing to the evaporating temperature. This power has to be added in evaluating the total heat input for the operation of a closed-cycle spacecraft system. Assuming a condensing temperature of 25° F, the total wattage thus determined, and plotted in Fig. 7, is seen to be well within the limits available from solar and nuclear sources.

IV. ENERGY BALANCE

The thermal power E required for the regenerative system of Fig. 1 can be written as follows:

$$E = E_1 + E_2 + E_3 + E_4 \tag{1}$$

where E_1 is the power required to raise the temperature of the liquid from the sump temperature in the condenser to the boiling temperature in the evaporator, E_2 is the power required for the enthalpy gain between the saturated liquid and the saturated vapor at operating pressure, E_3 is the power input for superheating, and E_4 is the total heat-power loss of the closed-cycle system to its surroundings.

The boiling temperature of a given Freon compound for a desired operating pressure can be read from the chart of Fig. 2. The increase in enthalpy, E_2, at this temperature for the transition from the liquid to the saturated vapor phase can be obtained from pressure-enthalpy diagrams which the DuPont Company has published for various Freon products. Figure 8 is an example of Freon-114.

It can be shown that E in Eq. (1) is a linear function of the mass flowrate W (but not a linear function of the pressure). In order to arrive at an estimate of E, the heat loss E_4 is assumed to be proportional to the difference Δt_1 between the vapor temperature and ambient (room) temperature; i.e.,

$$E_4 = \alpha \Delta t_1 \tag{2}$$

The experiments showed α to be indeed constant within the range investigated and to equal 0.52, if Δt_1 is measured in °F.

For calculating E_1 in Eq. (1), a sump temperature of 25°F was used. Since the experiments were carried out without superheating the Freon-114 vapor, E_4 in the energy-balance equation becomes zero.

In Fig. 9, the computed values for E for three flowrates, i.e., 0.0478, 0.0342, and 0.0211 cfm, are plotted as solid lines. The comparison with the measured power input, corrected to a room ambient temperature of 75°F, for these three flowrates (symbols) shows a degree of correlation which can be considered satisfactory in view of the limitations involved.

V. CONCLUSION

The conclusion can be drawn from this investigation that a closed-cycle system, using Freon or some other fluid with similar thermodynamic properties, is quite feasible for spacecraft applications of the type discussed. The thermal pumping power can be obtained directly from solar radiation (in panels or concentrators) or from nuclear reactors, if and when available. Condensation of the fluid is accomplished by exposing it to the dark side of the spacecraft. The liquid is returned to the evaporator by a miniature mechanical pump or by capillary action. It can be shown that the pumping power for the small liquid flowrates involved is negligible.

ACKNOWLEDGEMENT

The authors wish to express their appreciation to Mr. William T. Jones for constructing and operating the experimental closed-cycle system.

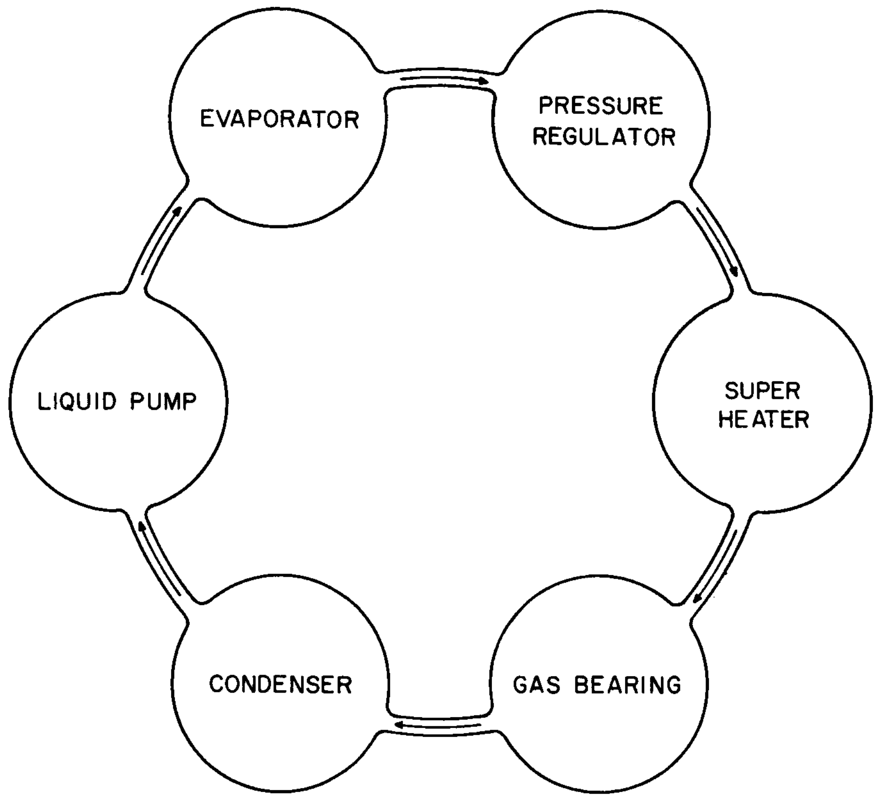

Fig. 1. Closed-cycle system diagram

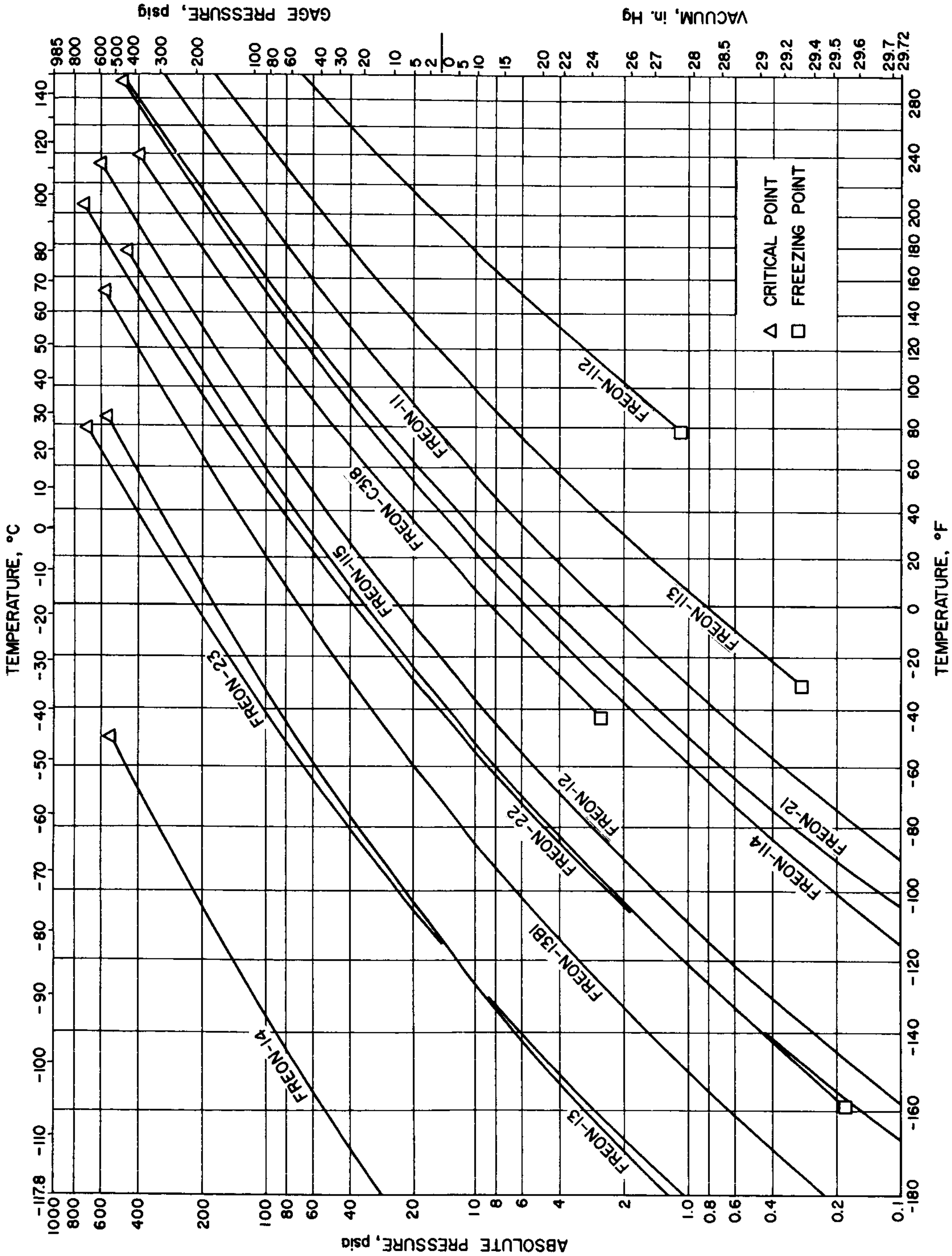

Fig. 2. Pressure-temperature relationships of Freon compounds

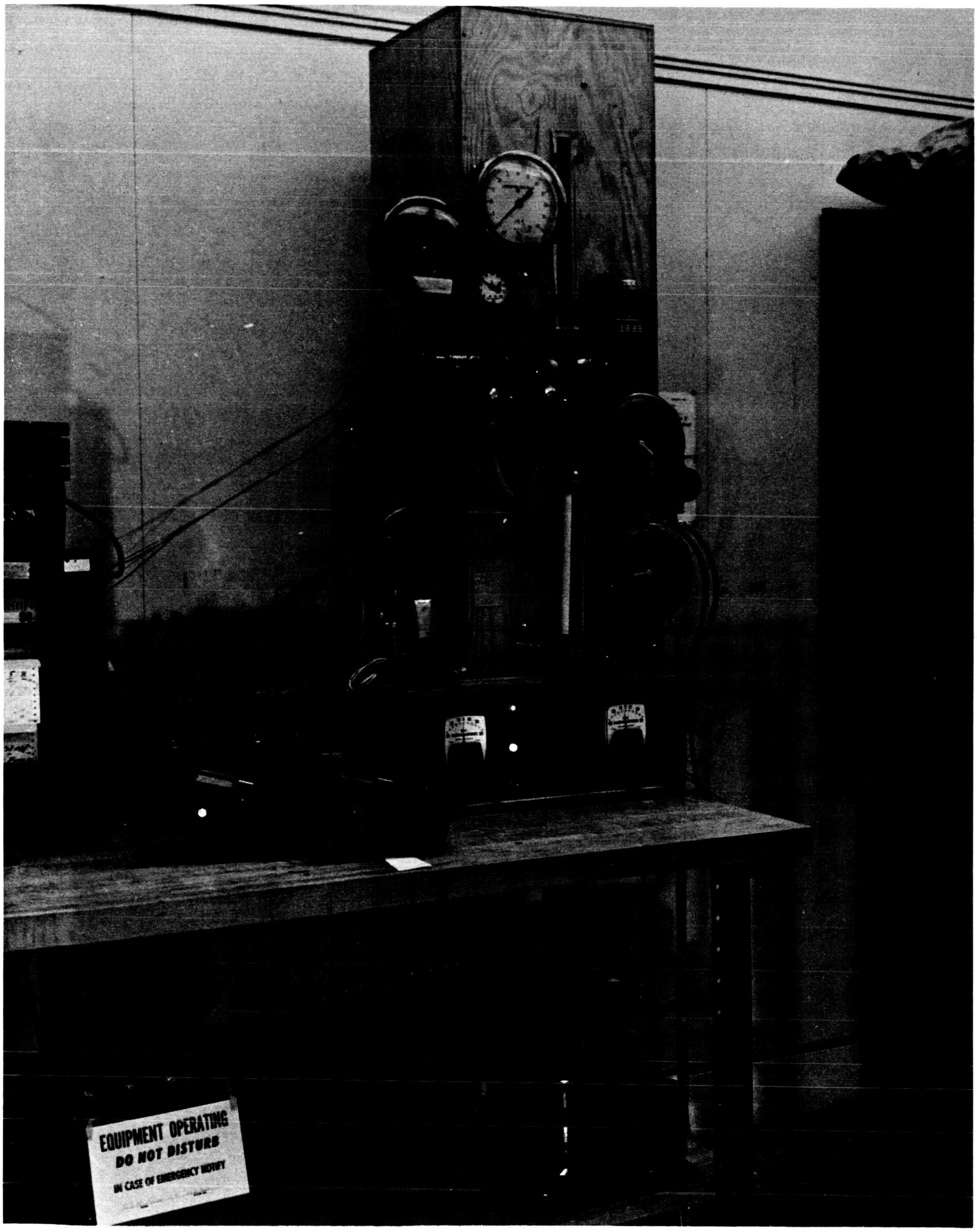

Fig. 3. Closed-cycle gas supply experimental arrangement

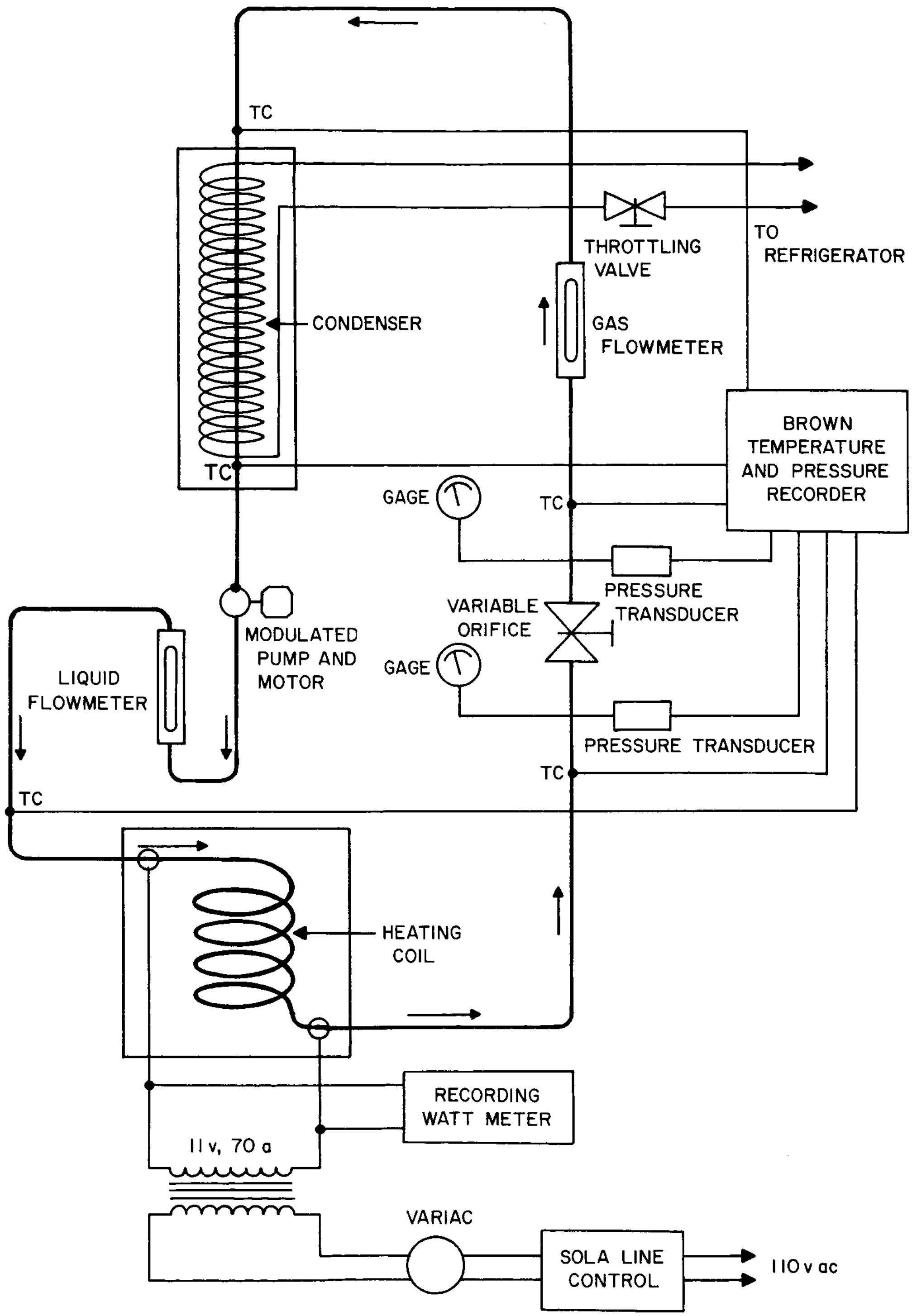

Fig. 4. Test equipment for liquid-gas closed-cycle system

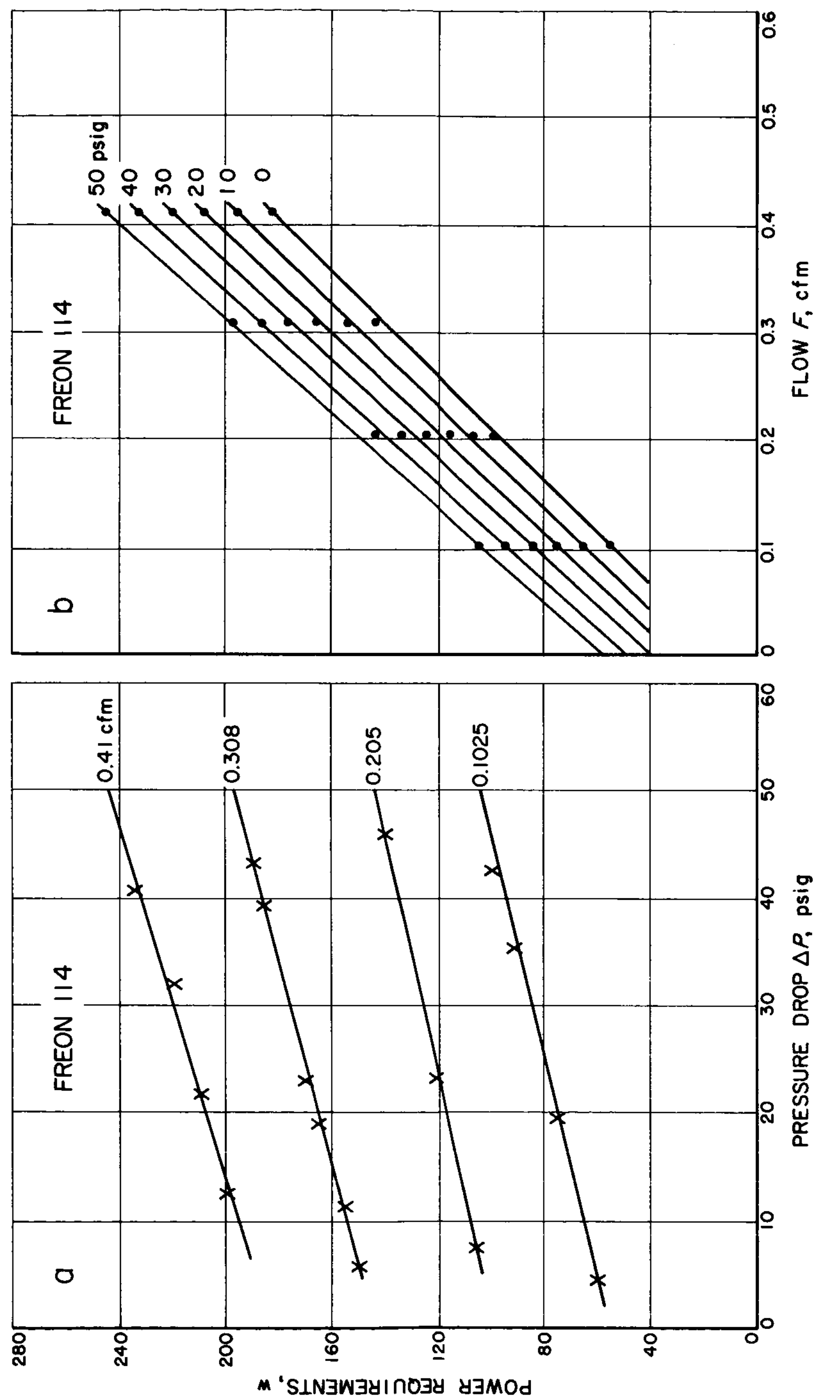

Fig. 5. Freon-114 thermal-pumping-power requirement as a function of pressure and flowrate

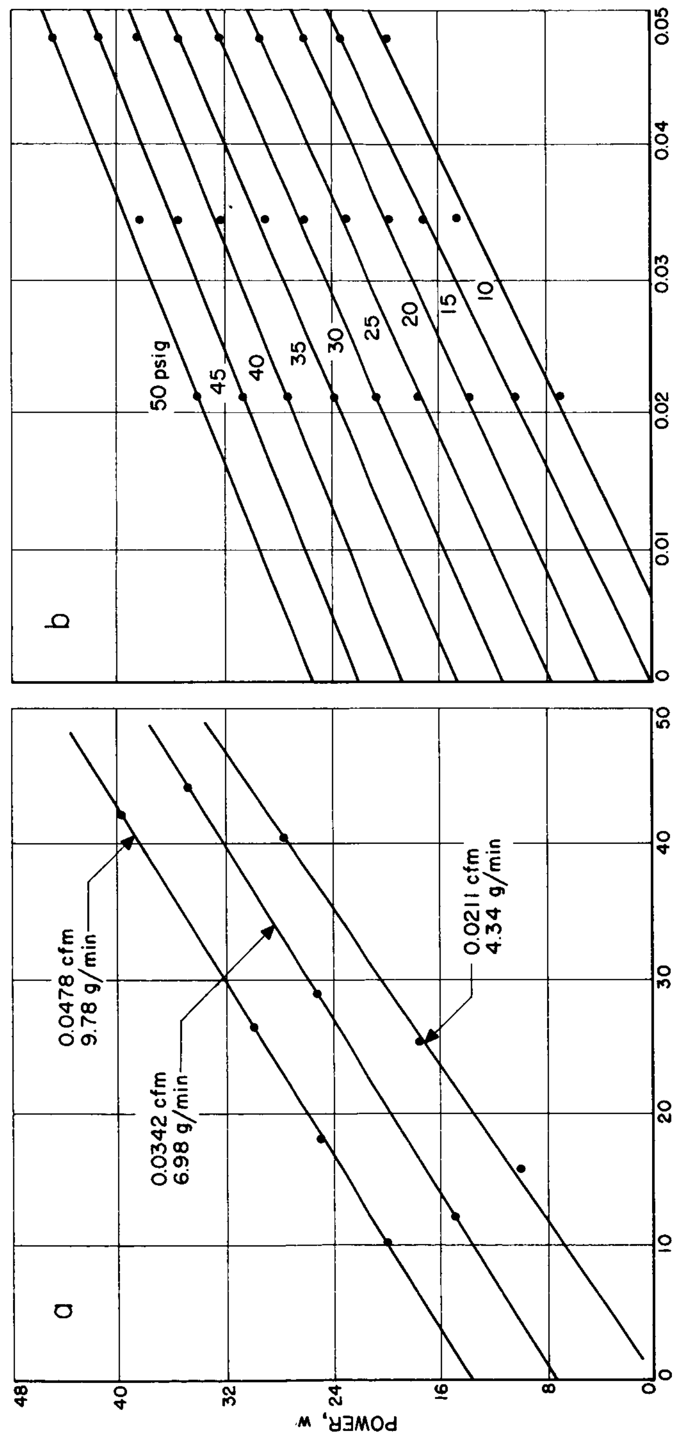

Fig. 6. Freon-114 power as a function of pressure and flowrate, low flow

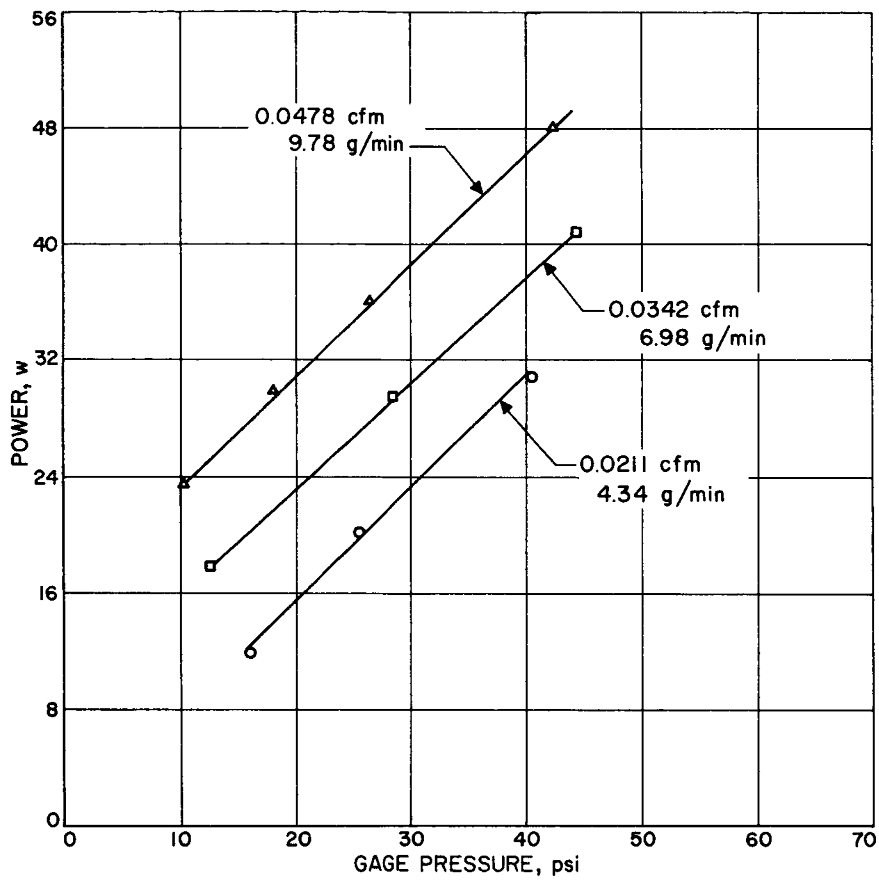

Fig. 7. Freon-114 thermal-pumping-power requirement as a function of pressure

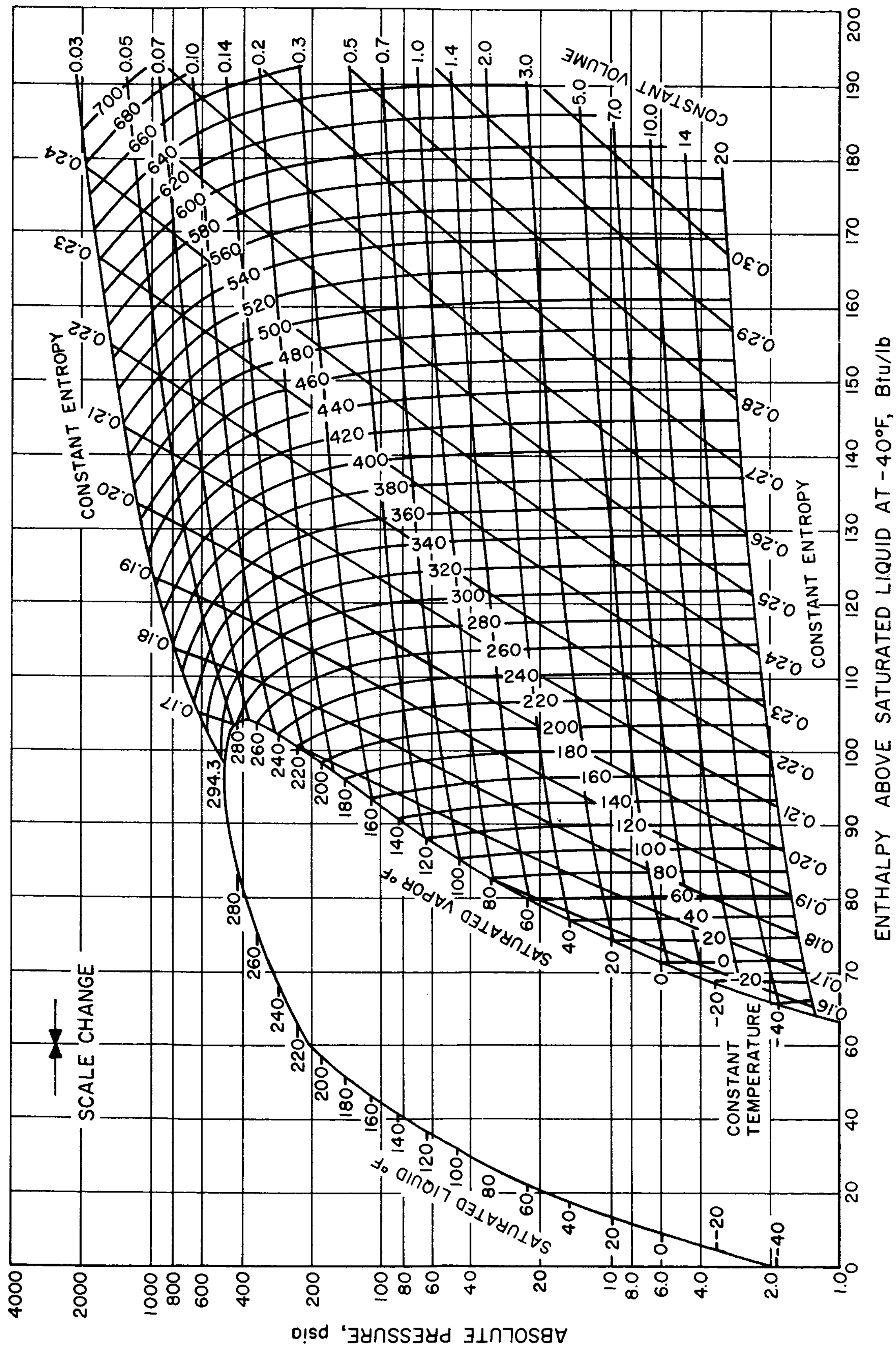

Fig. 8. Freon-114 pressure-enthalpy diagram

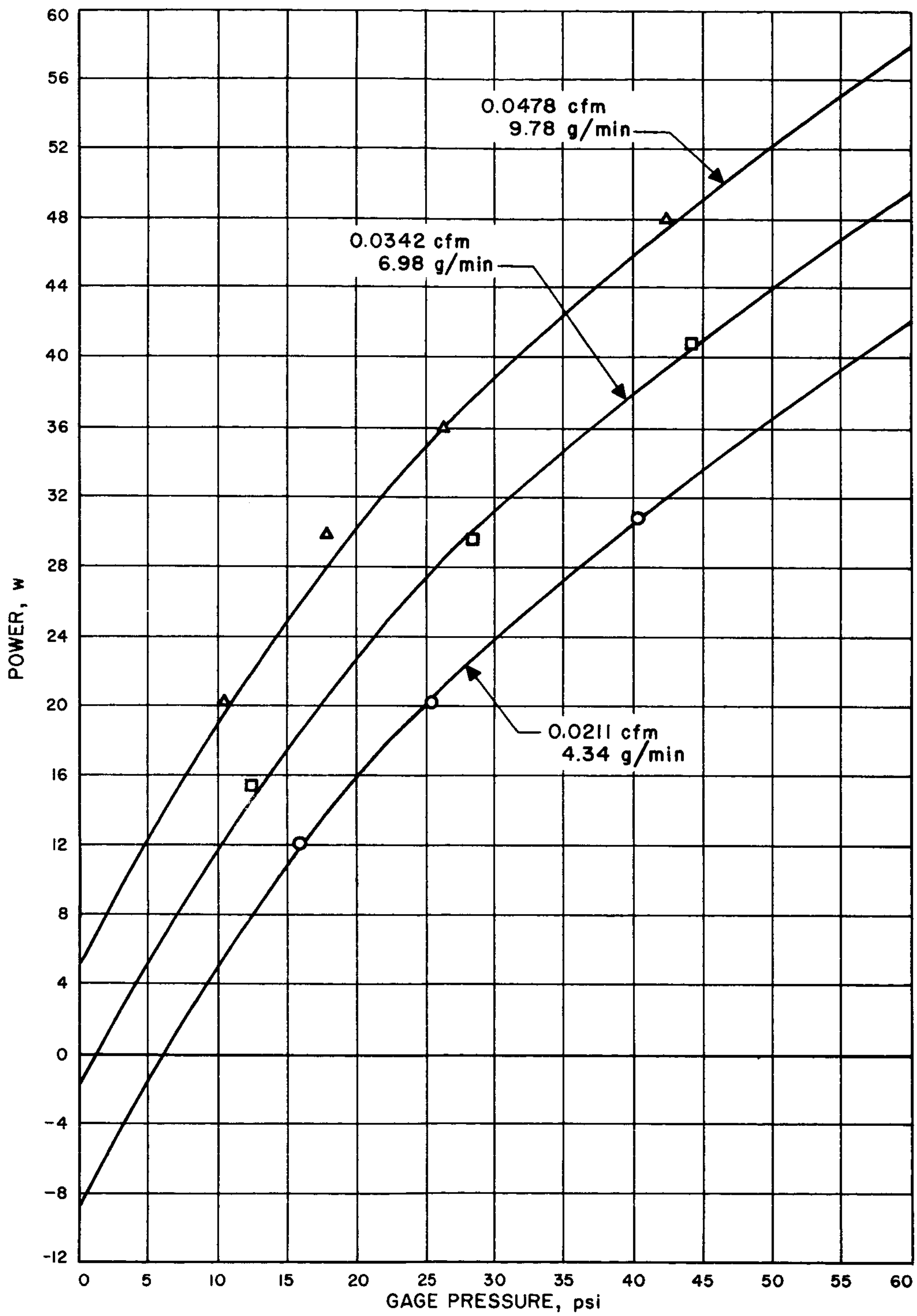

Fig. 9. Freon-114 thermal-pumping-power requirements; comparison of predicted and measured values